Magnetic Wires and Point Contacts

Next 2 lectures: Look at a variety of small structures with interesting magnetoresistance properties

One continuing theme: How sophisticated a model does one need to understand nanomagnetic devices?

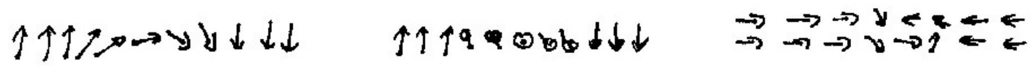
- Stoner Model OK?
- Stoner Model with "d" and "s" electrons?
- Real band structure / quantum states?
- Many-body electronic states instead of single electrons?

Will see that magnetism has lots of surprises – to understand even simple phenomena in detail, often need to go beyond simple models.

Topic 1: Thin wires with magnetic domain walls.

Different kinds:

Néel wall   Bloch wall   Vortex



tilt in plane   tilt out of plane

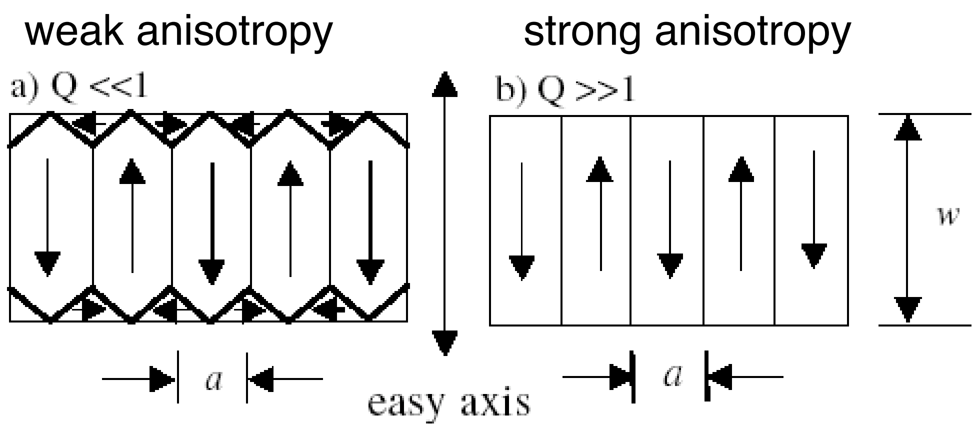
Structure determined by competition between magnetic dipolar energy, exchange, and magnetic anisotropy, and is sensitive to sample shape and magnetic field history

Width can range from atomic scale to >100 nm

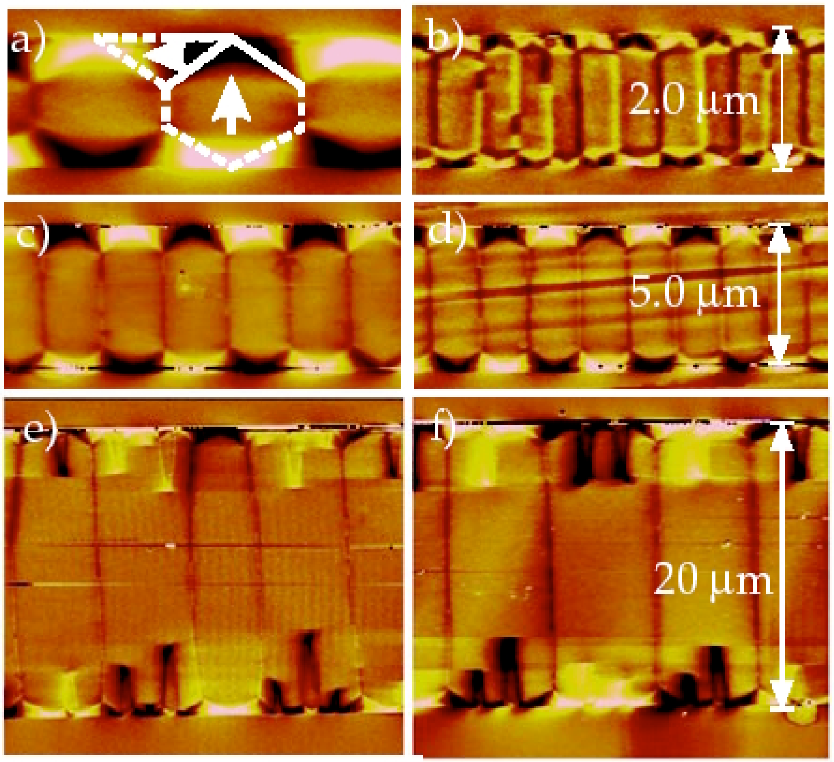
Will domain walls produce a GMR-like increase in resistance?
- junction between two magnetic regions oriented anti-parallel

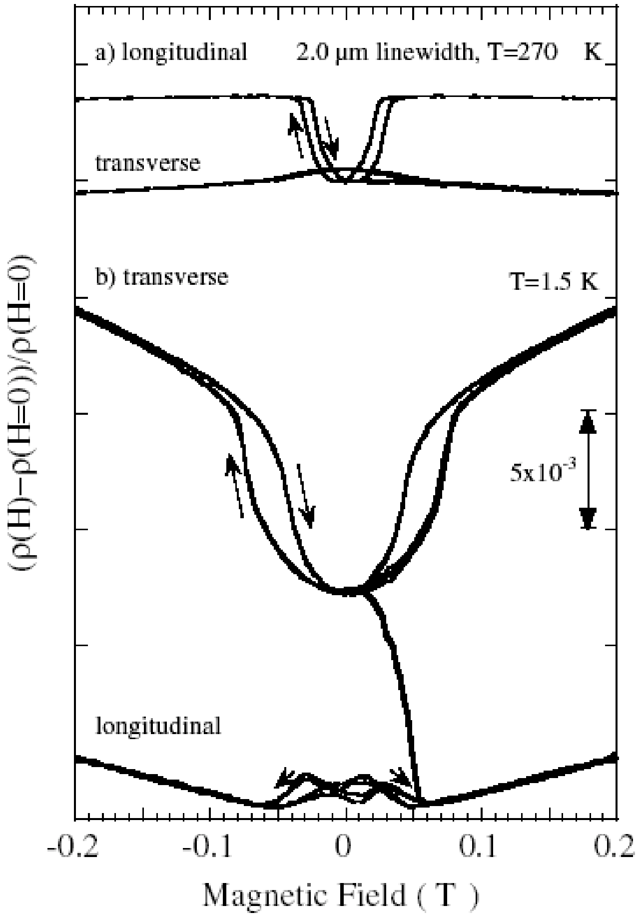
A. D. Kent et al.
J. Phys. Condens. Matter
13, R461 (2001)

epitaxial iron (110) wires
weak uniaxial anisotropy
stripe domains



after transverse saturation
after long. saturation





Results of Kent group experiment :

- presence of domain walls can make the resistance go either up or down!
- the direction in which the magnetization points makes more of a difference to the resistance than the existence of domain walls
- current parallel to $\vec{M}$ gives different resistance than current perpendicular to $\vec{M}$

(resistivity anisotropy)

Anisotropic magnetoresistance (AMR) - spin-orbit coupling

Lorentz magnetoresistance - classical bending of electron paths in the magnet's internal field

AMR : generally $\vec{J} \parallel \vec{M}$ gives larger resistance

LMR : $\vec{J} \perp \vec{M}$ gives larger resistance

] generally 1-2% effects

The two effects have different T dependences in Kent experiment - sign reversal as T is decreased.

Prior to this work lots of other experiments - some see domain walls giving increased resistance, some decreased. Lots of theories and proposed mechanisms

Domain walls might increase resistance :

- Domain wall scattering - like GMR. But size of the effect is much less than GMR because ordinarily the domain wall width is much less than the Larmor precession length of an electron in a magnet ⇒ the electron spin can follow the local magnetization direction adiabatically - Scattering only comes from a small amount of phase lag.

2-3 nm ↗

prediction : Levy & Zhang (PRL 79, 5110 (97))

resistance increase ~ 2% for domain wall width $\delta \sim 15$ nm typical of Fe, Co, Ni

↳ total resistance change much less adding resistance outside the domain walls.

Current ⊥ DW.

$$\boxed{R \propto \frac{1}{\delta^2}}$$

- current deflection due to Hall effect
  (zig-zag paths through stripe domains)

Domain Walls might decrease resistance:

- suppression of weak localization
- deflections of electrons away from surface scattering

Predictions the resistance could go either way:

- redistribution of charge among majority and minority bands, sign depends on relative relaxation times.

All very nice, but the bottom line is that unless special care is taken to eliminate resistivity anisotropy, it usually dominates and all of the other effects are smaller.

<u>e.g.</u> Change in resistance in Kent experiment can be understood quantitatively as due to the resistance change from the closure domains oriented perpendicular to the stripes.

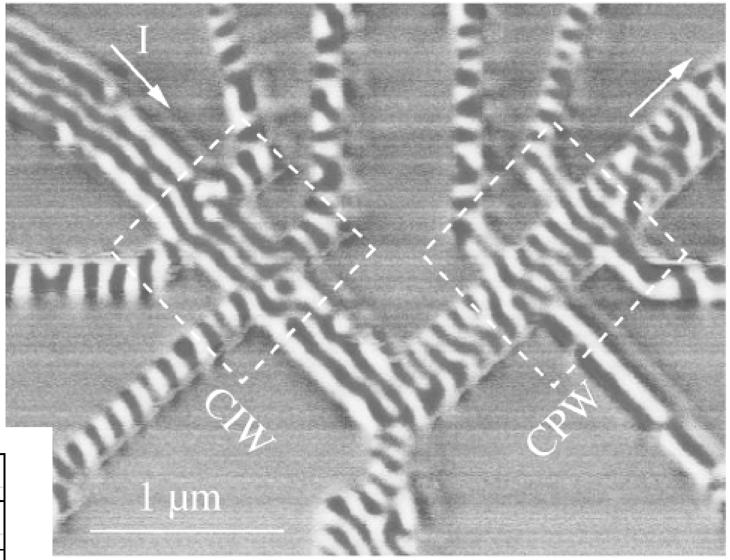
2 exceptions:

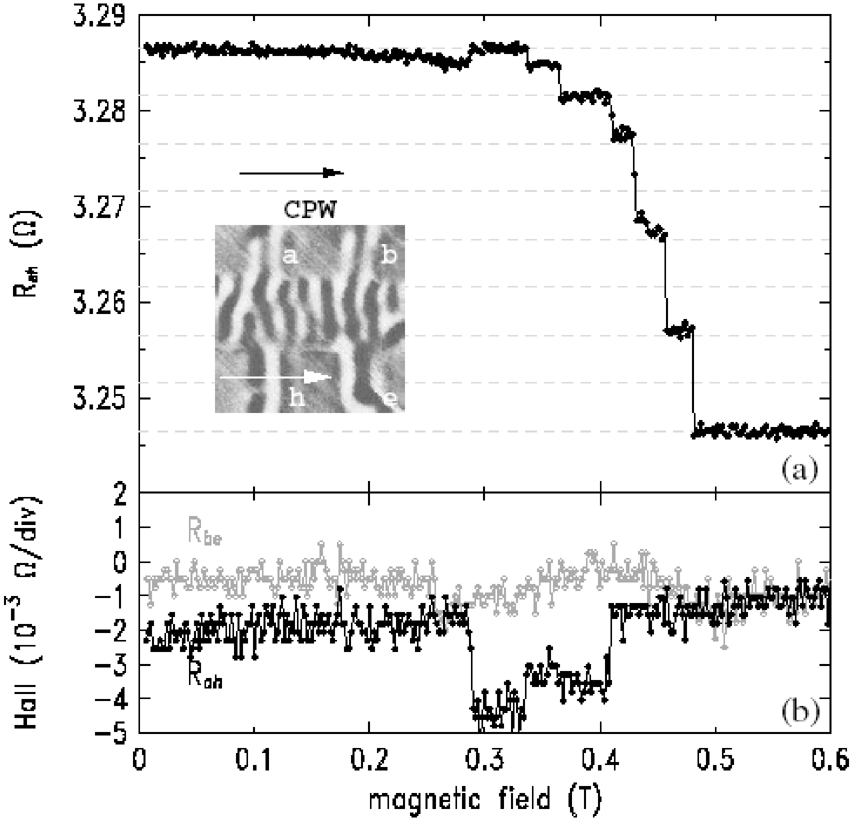
- samples with perpendicular anisotropy - moment can be kept always perpendicular to the current
- very small samples - very narrow domain walls
  (recall prediction Domain-wall scattering $\propto \delta^{-2}$.)

perpendicular anisotropy: see R Danneau, et al., PRL 88, 157201 (2002)

R. Danneau et al.
PRL 88, 157201 (2002).

FePd wires with very strong perpendicular anisotropy.
Stripe domains.
8 nm thick Bloch walls





5 mΩ reduction in R as each domain wall is eliminated by an applied field.

10% change in R over 8-nm wall thickness

General agreement with expectations from domain-wall scattering theories.

For physics of very small devices ("point contacts"), some interesting physics background.

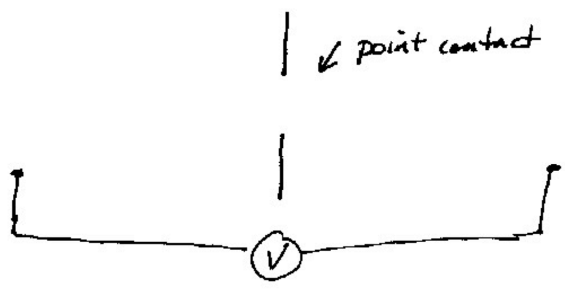
I will be discussing wires with lengths/widths from 1 atom to about 10 nm. This is much less than the inelastic scattering length, and even the mean free path ⇒ ordinary pictures of diffusive electron motion don't work

$$J \neq \rho E$$

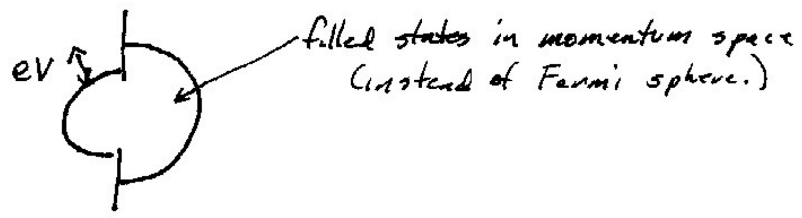
Will have hot electrons, nonlocal effects, etc.

For instance, instead of Fermi-Dirac distribution:

Model a "point contact" as an opening in an insulating membrane. Apply a voltage across the two sides


point contact

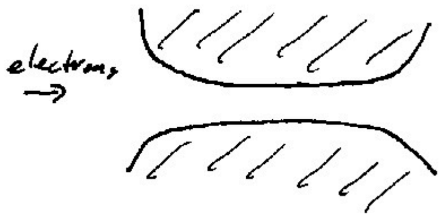
What is the electron distribution in the middle of the orifice?
Voltage will drop across the barrier on the length scale of the hole diameter.
Strong electric field on a scale less than the mean free path will accelerate electrons.
Allowed energy of the electrons will depend on what side they originated!



filled states in momentum space (instead of Fermi sphere.)

Good for spectroscopy. If a process requiring energy E can backscatter electrons, $\frac{V}{I(V)}$ will increase when $eV = E$.

Now suppose a slightly different model of a point contact: 1-d wire with adiabatic leads.

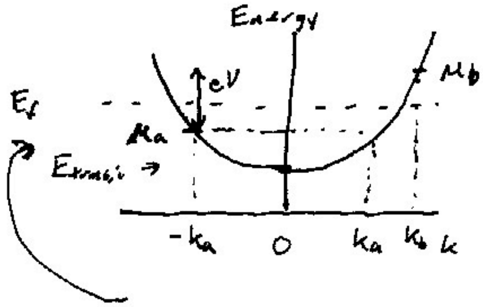


Assume nonmagnetic. Ignore electron interactions, Luttinger liquids, etc.

What is the resistance. Can model it as a waveguide - contains a certain number of quantized transverse electron modes each with propagating states along the channel

states in mode i : $\Psi_i(k,r) = \phi^{(r)}_{\text{transverse},i} \; e^{ik\cdot r}$ ↙ (or Bloch state)

energy $E_i(k) = E_{\text{trans},i} \frac{\hbar^2 k^2}{2m^*}$



← Parabola for free electrons. Could be more complicated in real life. I'll only need to assume time reversal symmetry $E_i(k) = E_i(-k)$

If there is an applied voltage, which electron states are occupied?

Assuming no scattering, how much current flows?

Semiclassically, can add the current from each occupied state

$$I = \underset{\swarrow\text{ spin degeneracy}}{\frac{2e}{L}} \sum_k v(k) \quad \leftarrow \text{group velocity}$$

↖ sum over occupied states spaced by $\Delta k = \frac{2\pi}{L}$

$$= \frac{2e}{L}\frac{L}{2\pi}\int_{-k_a}^{k_b} v(k)\,dk$$

. Note $\int_{-k_a}^{0}$ cancels with $\int_{0}^{k_a}$ by symmetry

$$= \frac{e}{\pi}\int_{k_a}^{k_b} v(k)\,dk$$

Convenient to convert to an integral over energy

$$dk = \underbrace{\frac{dk}{dE}}_{\text{(density of states)}} dE \qquad \text{group velocity} = \frac{1}{\hbar}\frac{dE}{dk}$$

$$I = \frac{e}{\pi}\int_{k_a}^{k_b} v(k)\,dk = \frac{e}{\pi}\int_{\mu_a}^{\mu_b} \frac{1}{\hbar}\frac{dE}{dk}\frac{dk}{dE}\,dE$$

group velocity cancels exactly with density of states for a 1-d channel, regardless of band structure!
→ high DOS means low group velocity.
per unit energy, each part of the band contributes the same amount to the current.

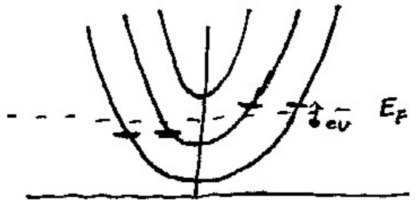
$$I = \frac{e}{\pi\hbar}\int_{\mu_a}^{\mu_b} dE = \frac{e}{\pi\hbar}(\mu_b - \mu_a) = \frac{e}{\pi\hbar}\,eV = \frac{2e^2}{h}V$$

no "ħ-bar"

Conductance $\frac{dI}{dV} = \frac{2e^2}{h}$, quantized for a single-mode ballistic channel with no scattering

Note this is not the conductivity. The conductance describes the entire device, regardless of length. (as long as there is no scattering)

With more than one transverse mode:



✓ will have $\frac{2e^2}{h}$ conductance per occupied channel

With scattering included, this picture can be generalized - Landauer formula.

$$\frac{dI}{dV} = \frac{2e^2}{h}\sum_{\substack{\text{occupied} \\ \text{"channels"}}} T_i$$

← transmission probability at the Fermi level.

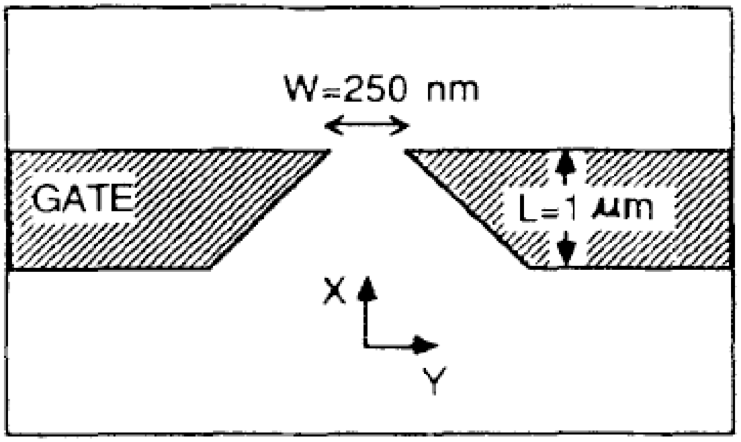
This works! semiconductor point contacts, Au and potassium point contacts.

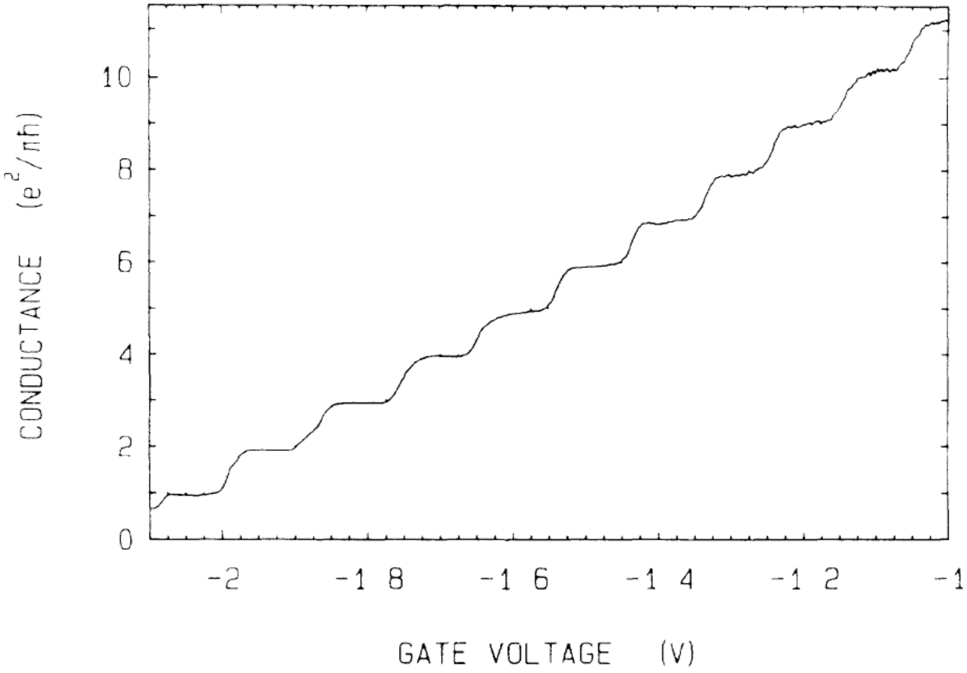
Factor of 2 comes from spin degeneracy. In a ferromagnet, this degeneracy is split. Expect quantization with steps of $\frac{e^2}{h}$ rather than $\frac{2e^2}{h}$?

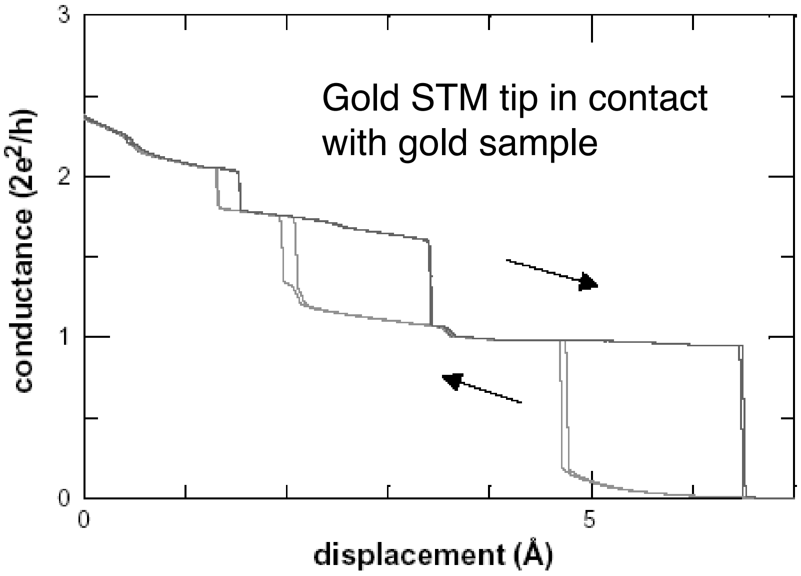
Quantized Conductance in a Semiconductor Point Contact

B. J. van Wees et al.
PRL 60, 848 (1988).

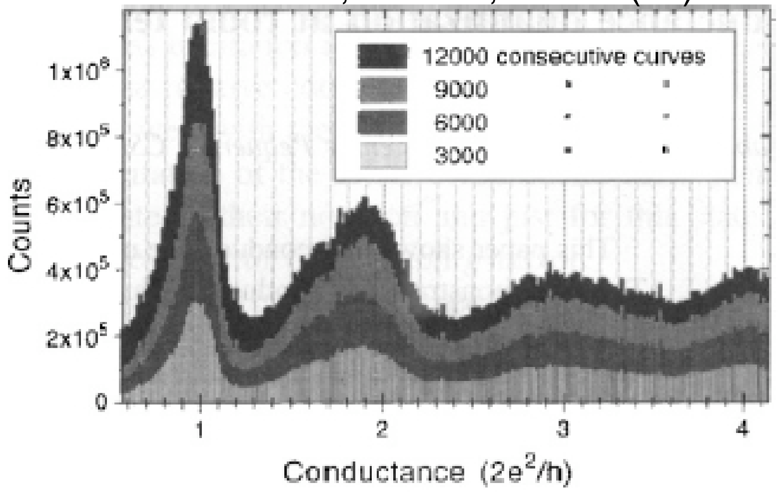
top view
of device.



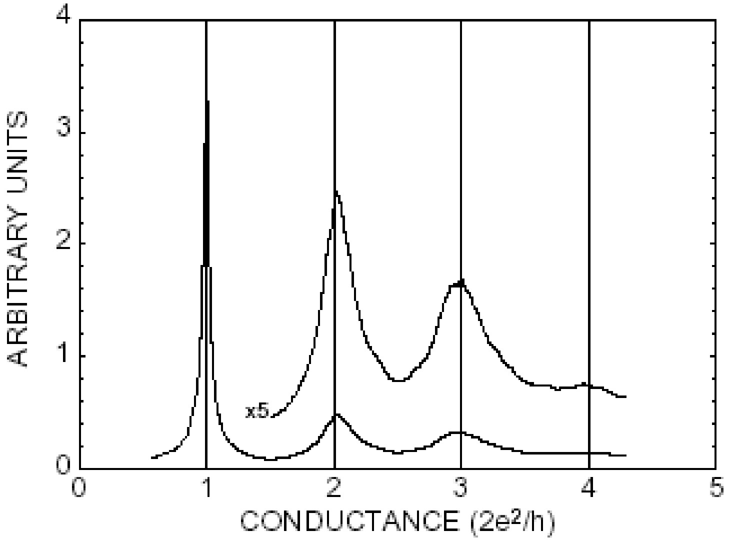



Gold STM tip in contact with gold sample

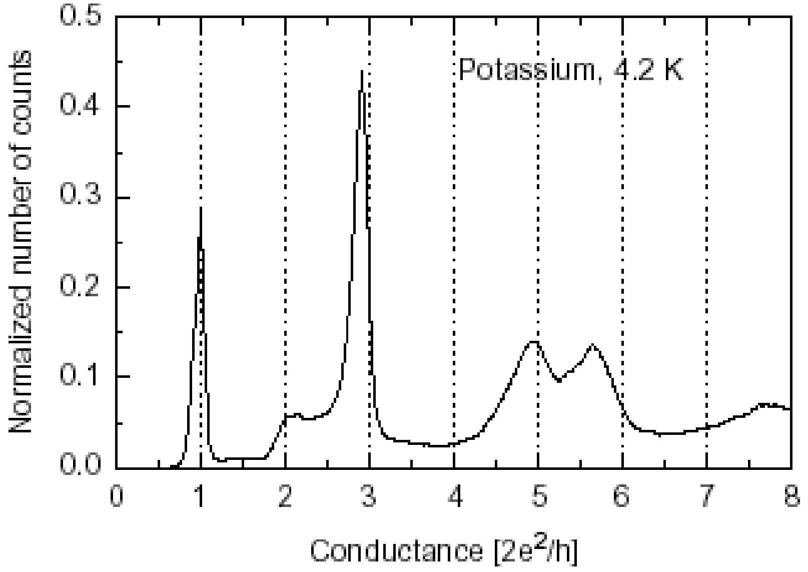
Gold in air at room temp.
J. L. Costa-Krämer, PRB 55, R4875 (97)

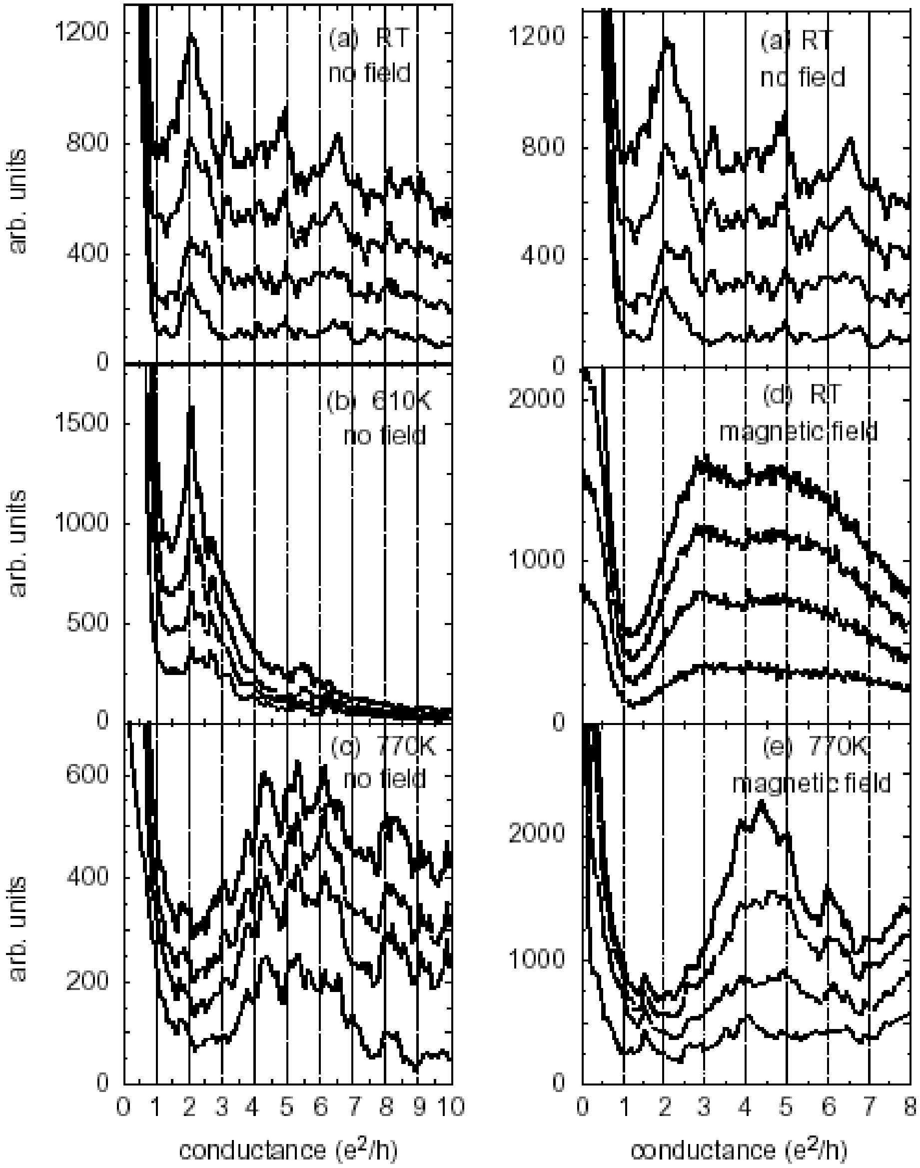


Gold in UHV at room temp.
M. Brandbyge et al., PRB 52, 8499 (95)



A. I. Yanson, Ph.D. thesis, Leiden 2001



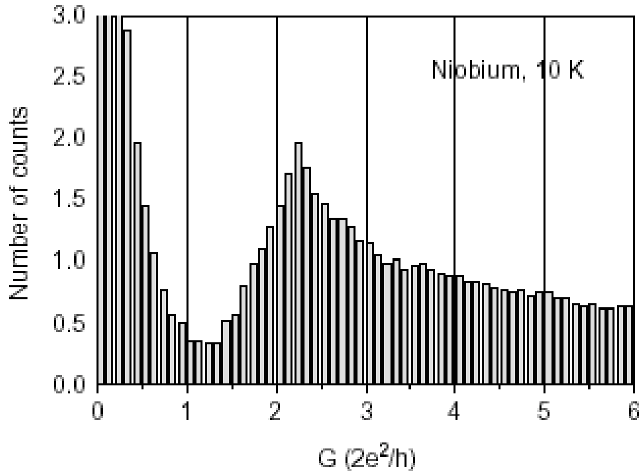


Nickel contacts
H. Oshima et al., APL 73, 2203 (1998)

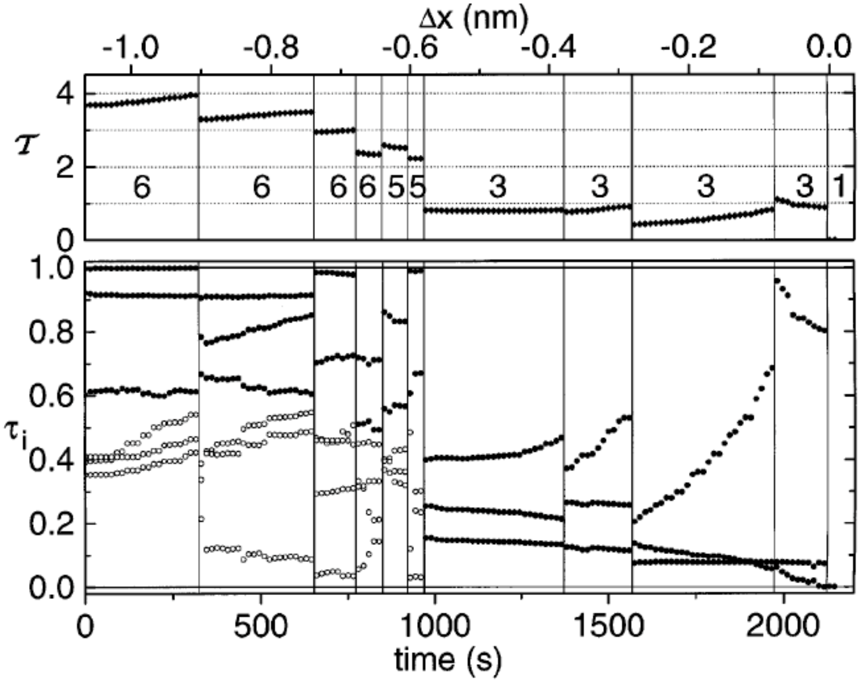
No consistent conductance quantization, at least when the nickel is saturated in an applied magnetic field.

But actually, good quantization is not observed for nonmagnetic transition metals.

B. Ludoph et al., PRB 61, 8561 (2000)



The existence of real atoms matters. When there are lots of s, p, d orbitals per atom, there are lots of partially conducting channels even in a single-atom point contact.

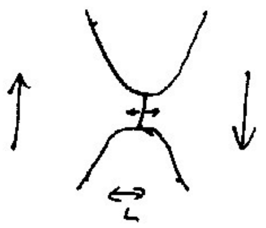


The individual transmission coefficients can be characterized separately using tricks with superconducting contacts or noise measurements.

E. Scheer et al., PRL 78, 3535 (1997)
Data from an aluminum point contact.

That was a bit of an aside, now back to the question of domain walls.

Another of the interesting features of point contacts is that they should support very narrow domain walls.



Suppose you start with an infinitely narrow domain wall in the constriction

Expensive in exchange energy - will want to spread out.

How much? If it spreads much more than $\delta \approx L$ the region of tilted spins must expand to a large region, much longer domain wall - expensive in both anisotropy and dipole energies

$\Rightarrow$ expect domain wall width $\delta \approx L$ - could be down to atomic scales. Recall domain wall scattering expected $\propto \frac{1}{\delta^2}$.

What are the effects of domain walls in this regime are still controversial, but there are some very intriguing results.

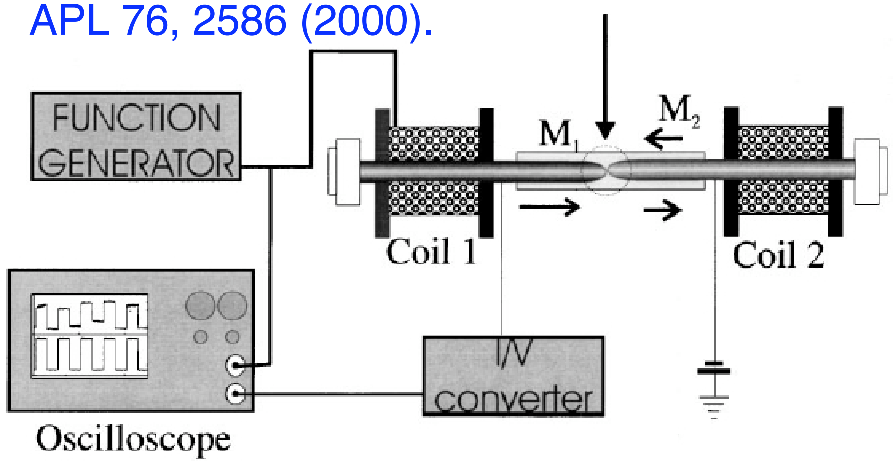
If the effects are real, there are some proposed explanations

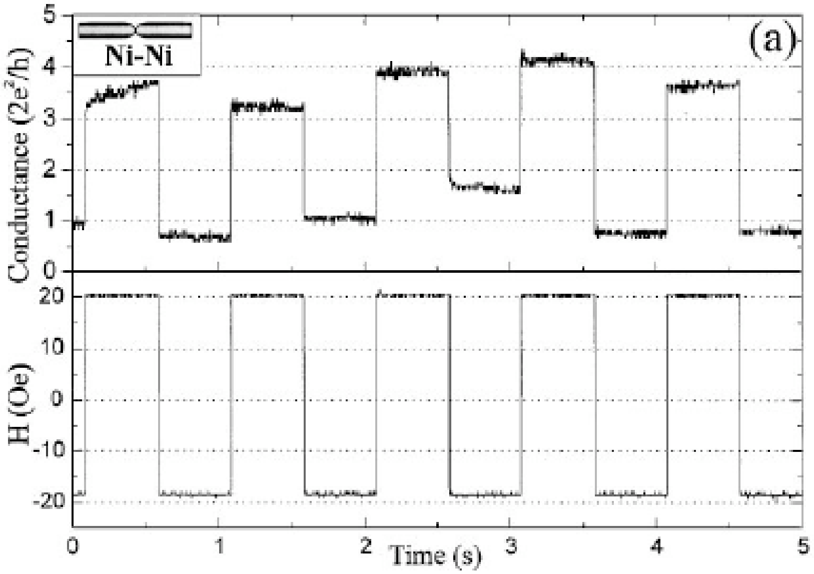
- Greater contribution of d states over s states, relative to tunneling or GMR. (Tatara)
- Domain wall could change electronic structure within point contact - shift nearly-degenerate d-states away from Fermi energy (van Hoof)
- Unusual magnetic states in atomic scale wires?
  e.g. $\uparrow)\ \textcircled{\downarrow}\textcircled{\uparrow}\ (\downarrow$

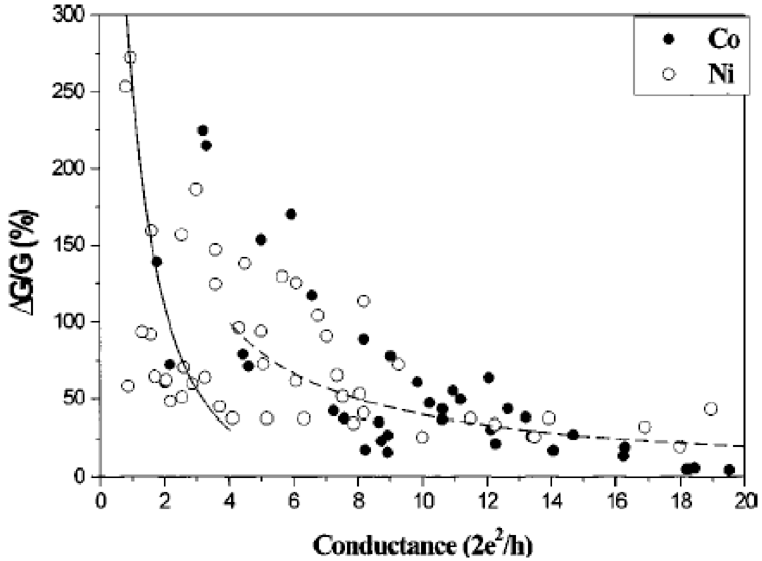
No quantitative theories yet. Both experimental and theoretical situation still unsettled.

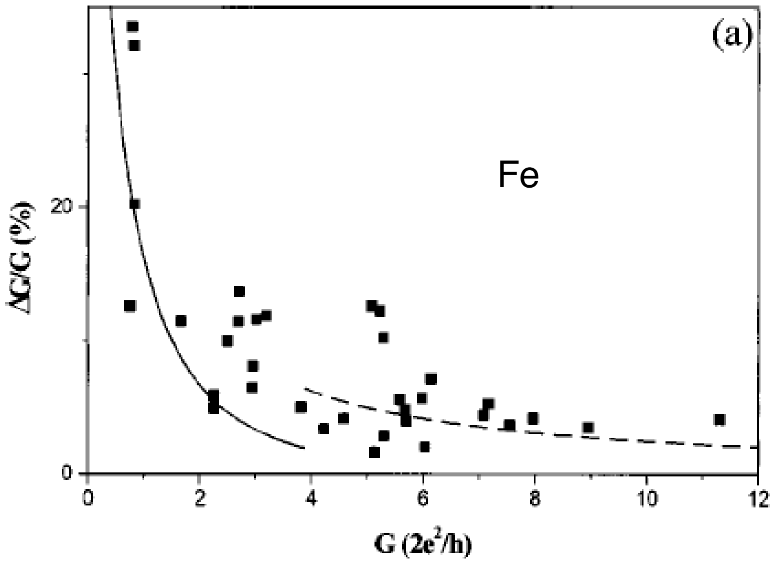
N Garcia et al., PRL 82, 2923 (1999),
APL 76, 2586 (2000).

Compare: CPP GMR in Co/Cu: ~ 120%
TMR in tunnel junctions: ~ 60%



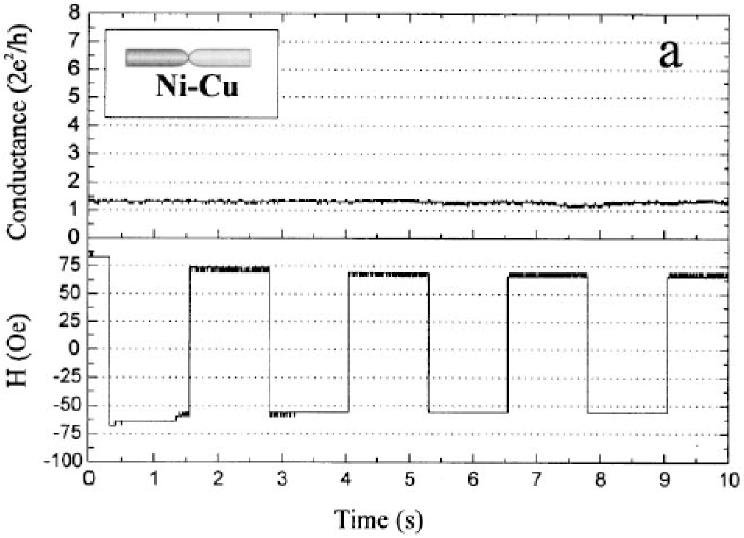






Even bigger changes (100,000%) reported by S. Z. Hua and H. D. Chopra, PRB 67, 060401 (2003), but I suspect that their contacts might be breaking.

Magnetostriction?

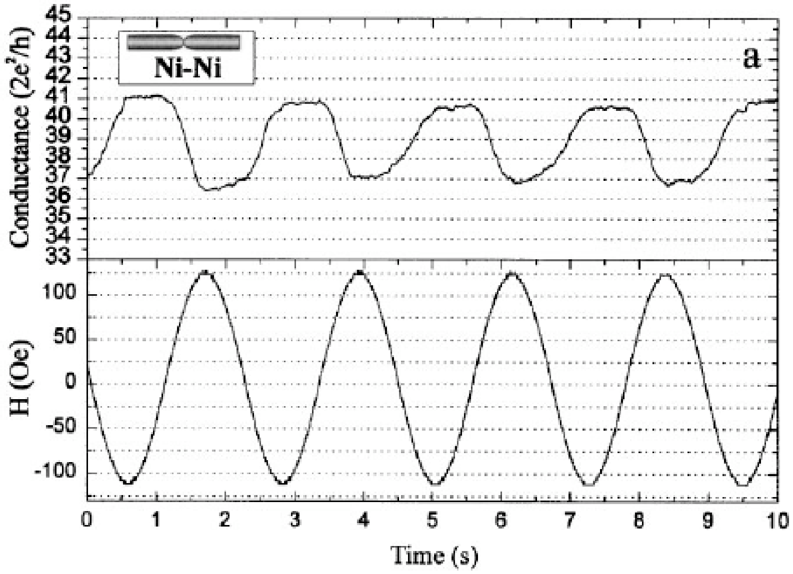


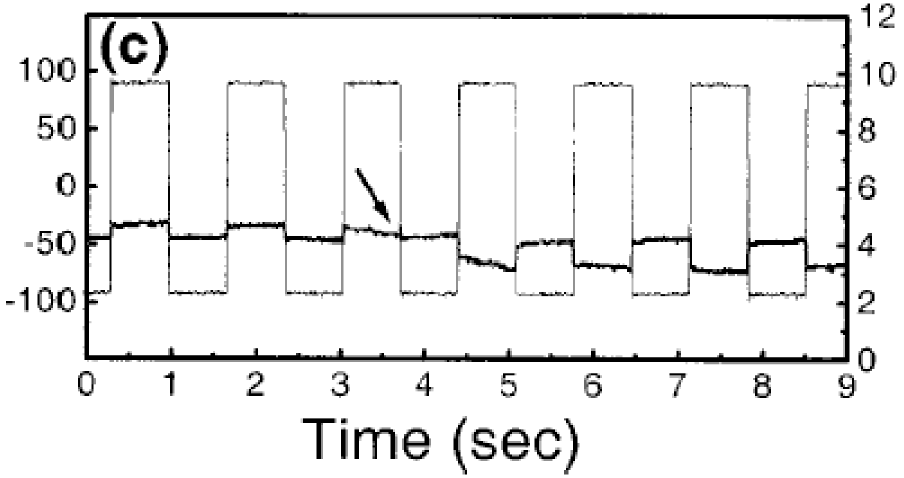
No effect for Ni against Cu

Magnetoconstriction should go as
the square of the applied field.

Effect is there for non-magnetic metals
coated with a thin film of ferromagnet

Phase changes when the fixed moment
is flipped.



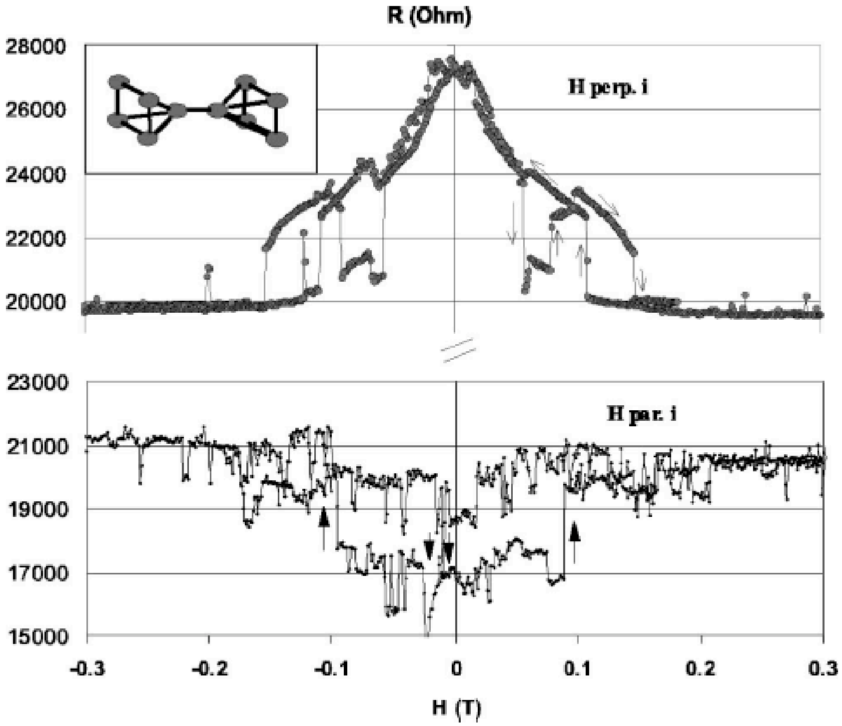


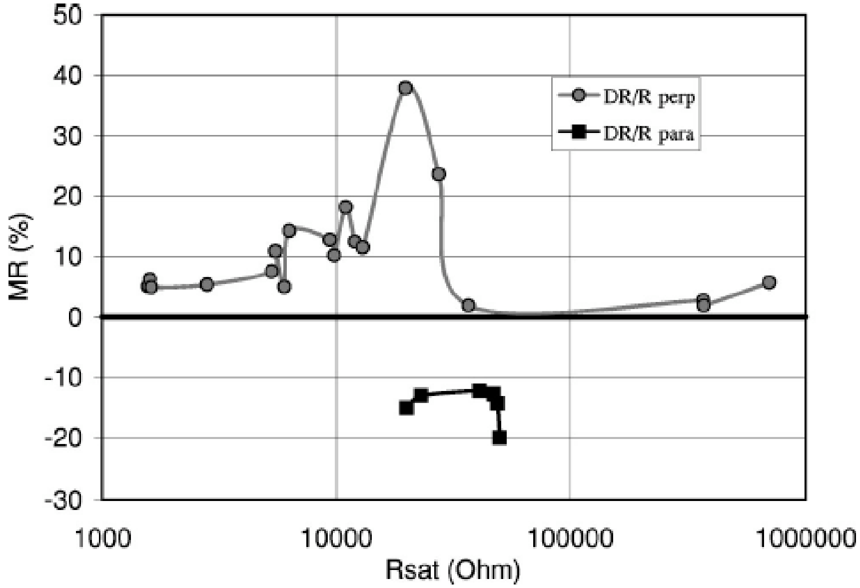
But I am still suspicious of the results. It appears that all of the experiments have been done at room temperature either in air or electrolytic solution. Surface contamination? Oxides?

Magnetic forces might move the wires slightly in the contact region and change R.

Contact geometry and magnetic state are not well characterized. (this is hard)

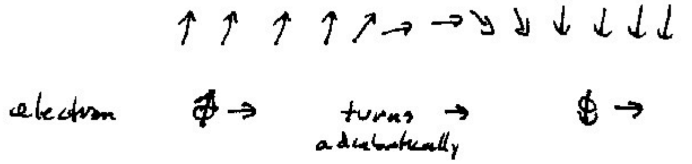
Experiments in vacuum at low temperature have so far seen much smaller effects.



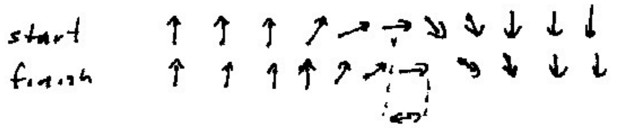


M. Viret et al., PRB 66, 220401 (2002)
Ni mechanical break junction

Spin-Transfer Torques and Domain Walls.



⇒ Domain wall applies a torque on the electron, must feel back-action torque.
Torque on the domain wall is in the direction to push the moments ↑.
This has the effect of acting to shift the domain wall in the direction of the electron velocity



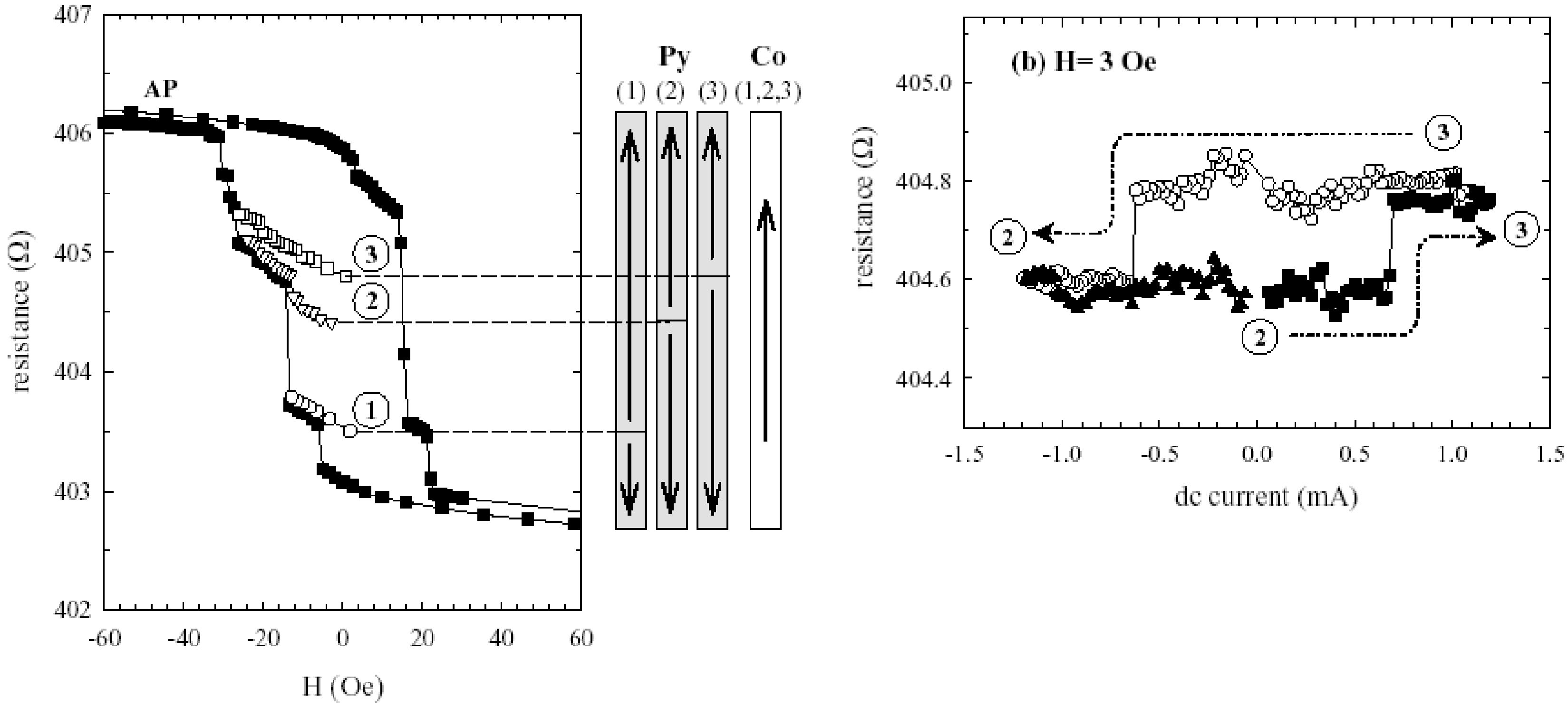
predicted: L Berger J. Appl Phys 55, 1954 (1984)
observed with current pulses in macroscopic films: Freitas and Berger, J. Appl. Phys. 57, 1266 (1985); Hung and Berger, J. Appl. Phys. 63, 4276 (1988).

This field is now becoming reinvigorated - can nanofabricate good magnetic wires and employ tricks to manipulate the position of individual domain walls.

Can push domain walls around using only spin-polarized currents, at zero applied magnetic field. (Grollier et al. cond-mat/0304312)
current densities comparable to or even lower than switching current in multilayer pillars.

J. Grollier et al., cond-mat/0304312 (2003)

Manipulating domain walls in permalloy wires using a spin-polarized current.



Summary:

The resistance of most domain walls is dominated by resistivity anisotropy rather than simple scattering of electrons from the domain wall

With resistivity anisotropy, the resistance of wires with domain walls can be either more or less than wires without.

Effects of resistivity anisotropy can be eliminated for wires with strong perpendicular anisotropy or (possibly) in atomic-scale point contacts. In these situations, scattering of electrons from the domain wall can give a small increase in resistance.

Atomic-scale magnetic point contacts do not show simple conductance quantization with steps of e^2/h.

Huge magnetoresistance signals have been reported for atomic-scale magnetic point contacts - Due to atomic scale domain walls? Still controversial.

Spin-polarized currents can move domain walls.

References for Magnetic Wires and Point Contacts

A. D. Kent et al., Domain wall resistivity in epitaxial thin film microstructures, J Phys.: Condens. Matter 13, R461 (2001)

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A. Brataas et al., Ballistic and diffuse transport through a ferromagnetic domain wall, PRB 60, 3406 (99)

N. Agrait et al., Quantum properties of atomic-sized conductors Physics Reports 377, 81 (2003).

H. Oshima & K. Miyano, Spin-dependent conductance quantization in nickel point contacts, APL 73, 2203 (98)

S. H. Chung et al., Universal scaling of magnetoconductance in magnetic nanocontacts, J. Appl. Phys. 93, 7939 (2003).

M Viret et al., Magnetoresistance through a single nickel atom PRB 66, 220401 (2002)

G. Tatara et al., Domain wall scattering explains 300% ballistic magnetoconductance of nanocontacts, PRL 83, 2030 (99)

J. B. A. N van Hoof et al., Ballistic electron transport through magnetic domain walls, PRB 59, 138 (99)

L. Berger, Exchange interaction between ferromagnetic domain wall and electric current in very thin metallic films, J. Appl. Phys 55, 1954 (1984)

P. P Freitas and L. Berger, Observation of s-d exchange force between domain walls and electric current in very thin permalloy films, J Appl. Phys. 57, 1266 (1985)

X. Waintal and M. Viret, Current induced distortion of a magnetic domain wall, cond-mat/0301293

J. Grollier et al., Switching a spin valve back and forth by current-induced domain wall motion, cond-mat/0704312